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# An Experimental Test to Compare Viability of Various Theories of Atmospheric Velocity Fluctuations

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Several theories of velocity fluctuations in the atmsophere are discussed in the context of the horizontal wavenumber power spectral density (PSD). The main purpose of this report is to provide an experimental method to decide the question of which of these various theories are viable. The presently existing explanations of this PSD fall into the following categories: (a) quasi-two-dimensional turbulence theories as proposed by Gage and by Lilly; (b) theories of waves in cascade as proposed by Dewan; (c) "separable" gravity wave theories which explain horizontal wavenumber PSD slopes in terms of vertical wavenumber and temporal frequency PSD slopes, as proposed by Gardner et al., and (d) the diffusive filtering theory, as proposed by Gardner. The experimental test proposed in this report is based on the horizontal wavenumber PSD observations of Nastrom and of Bacmeister et al, who reported that, under certain circumstances, this PSD exhibited a change of slope (going from -5/3 to -3) as the wavenumber increased.

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# AN EXPERIMENTAL TEST TO COMPARE VIABILITY OF VARIOUS THEORIES OF ATMOSPHERIC VELOCITY FLUCTUATIONS

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## Abstract

This report proposes an experimental method to decide which of a number of theories of atmospheric velocity fluctuations are viable. The theories to be considered all make definite predictions concerning the horizontal wavenumber power spectral density (PSD) of horizontal velocity fluctuations. The presently existing explanations of this PSD fall into the following categories: (a) quasi-two-dimensional turbulence theories; (b) theories of waves in cascade; (c) "separable" gravity wave theories that explain horizontal wavenumber PSD slopes in terms of vertical wavenumber and temporal frequency PSD slopes; (d) the diffusive filtering theory; and (e) a fifth purely empirical model will also be discussed. The experimental test proposed is based mainly on the horizontal wavenumber PSD observations of *Nastrom et al.* (1987) and *Bacmeister et al.* (1996) who reported that, under certain circumstances, this PSD exhibited a change of slope (going from -5/3 to -3) as the wavenumber increased. The key factor is the actual wavenumber where this change of slope or "spectral break" occurs and the dependence of this wavenumber on altitude. Theories in class (a) predict that the altitude dependence of the wavenumber for the change in slope is such that the wavenumber decreases with altitude. Theories in class (b) say that the dependence is exactly the opposite; that the wavenumber increases with altitude. Those in class (c) also predict a change of slope occurring at a

wavenumber that decreases with altitude [as in case (a)], but this wavenumber, unfortunately, is ten times larger than the observations indicate. Theory (d) does not predict a change of slope of any kind. Model (e) predicts a change dependent on static stability. Theories (a) - (c) thus fall into two main groups, namely, those which predict the horizontal wavenumber of the slope change to grow with altitude and those which predict the opposite. The advantage of performing an experiment to measure the actual altitude dependence on horizontal wavenumber of the change in slope is that there is a qualitative difference in the theoretical predictions. For this reason the outcome should be robust and definitive provided the proper controls explained here are in place.

## 1. INTRODUCTION

This report proposes a definitive experimental test to decide between two classes of theories of atmospheric velocity fluctuations. In general, physical theories can play a number of roles, two of which are (a) the interpretation of existing experimental data and (b) the suggestion of specific experiments for testing a theory or for deciding between competing theories. In the present case we are interested in the latter. Five types of theories are available to predict the altitude dependence of a certain property of atmospheric velocity fluctuation spectra, and, fortunately, two of them give rise to a qualitatively opposite prediction from the third one. The fourth one is non-committal. The fifth case predicts a dependence mainly with stability.

In particular we will be considering the horizontal wavenumber spectra of horizontal wind fluctuations of the kind that can be obtained from aircraft measurements. Only five types of theories currently exist to explain such spectra, namely (a) quasi-two-dimensional turbulence theories (Q2DTT) (*Gage*, 1979; *Lilly*, 1983); (b) the saturated cascade gravity wave theory (SCT) of *Dewan* (1997) and its predecessors (*Dewan*, 1979; 1991; 1994); (c) the separable gravity wave theories (SGWT) discussed in *Gardner et al.* (1993); (d) the diffusive filtering theory (DFT) of *Gardner* (1994); and (e) the empirical model for the ocean due to *Garrett and Munk* (1975), modified by *van Zandt* (1982) (GMV). The Q2DTTs predict a horizontal wavenumber, $k_x$, horizontal velocity spectra that has a $k_x^{-5/3}$ dependence. This two-dimensional turbulence has a "reverse cascade", which explains the observed power law, and the source is at the smallest scale while the energy goes from there to the largest scales. The SCT assumes that the waves interact in a non-linear way such that the energy cascades from large scale to small scale (as in inertial range turbulence). Again, there is a $k_x^{-5/3}$ shape predicted for this spectrum. The SGWT again

predicts a $k_x^{-5/3}$ shape, but in this theory one must assume a spectral index of -2 for the frequency spectrum to get this result. Such a spectral index, however, is consistent with experiment. The DFT also produces a $k_x^{-5/3}$ dependence again, and this is also true of the Garrett-Munk spectrum if suitably modified for the atmospheric case (private communication, Tom van Zandt, 2001; see also *van Zandt*, 1982). Hence all five approaches predict the same spectral shapes for the horizontal wavenumber spectrum of horizontal velocity fluctuations. It is, however, when there are spectral breaks that differences arise between the various theoretical predictions. The proposed experimental test of the report's title is based exclusively on this aspect of the PSD. This test consists of measuring the altitude dependence of the wavenumber of the spectral break; and it will be shown below that it can be used to separate the viable theories from the non-viable ones. Further discussion, however, requires some background information.

## 2. THE SPECTRAL BREAK OBSERVATIONS IN THE HORIZONTAL WAVENUMBER SPECTRA

The aircraft measurements of horizontal velocity fluctuations and the resulting horizontal wavenumber spectra that were published from HICAT (*Crooks et al.*, 1968) and PEM (*Cho et al.*, 1999a) did not show any breaks or changes of slope. These authors reported only spectral shapes consistent with a $k_x^{-5/3}$ dependence. [*Cho et al.* (1999b) also gave evidence for the presence of Q2DTT.] In contrast, consider Figure 1 from *Nastrom et al.* (1987) who reported results from the GASP program that used measurements from commercial aircraft. Figure 1, which is based on their Figure 6, utilized a small subset of their data which was restricted to cases where there were high winds over mountains in the neighborhood. The figure is further segmented to separate tropospheric and stratospheric data. As *Nastrom et al.* (1987) pointed out, there are transition scales where the PSD slopes change from -5/3 to -3 as one progresses to higher wavenumbers. These occurred at a wavelength of 23 km for the troposphere (nominal altitude 10 km) and at a wavelength of 15 km for the stratosphere (nominal altitude of 13 km) (*Nastrom*, 1999, private conversation).

It should be emphasized that the majority of the published spectra of this type do not contain these breaks. Instead, the breaks seem to occur only when there is an obvious, relatively nearby source of gravity waves as in the case, mentioned above, of *Nastrom* (1987).

*Bacmeister et al.* (1996) also saw a similar break in their horizontal velocity fluctuation, horizontal wavenumber spectra. They reported a slope change from -1.5 to -2.0 (i.e. consistent with -5/3) before the break to -3 at wavenumbers higher than the break. The wavelength of the break was around 3 km and the altitude of the measurements was at 20 km. The latter altitude required an ER-2 aircraft, i.e. a modified U-2. At such a high altitude there probably would have

been a higher likelihood of influence from a low altitude gravity wave source than what would generally be the case for commercial aircraft. *Gao and Meriwether* (1998) also measured such horizontal wavenumber spectra at 6-km altitude (mostly over water) and saw no breaks in their horizontal wind spectra. They did see a break in the spectra of the vertical wind fluctuations, however. We presume this break may not have been tied to gravity wave sources since their data were obtained over water and no gravity wave sources were reported.

The above observations suggest that if there is a strong, nearby source of gravity waves (GWs) there will be a break in the horizontal wavenumber spectrum of the horizontal winds and that this break will occur at smaller wavelengths as the altitude above the source is increased (see Table 1). Unfortunately, these observations could be misleading due to the fact that they were not done at a single geographic location at a single time.

Table 1. Altitude Dependence of Breaks in the Horizontal Wavenumber Spectra

| **Region** | Troposphere | Stratosphere (lower) | Stratosphere (higher) |
|---|---|---|---|
| **Altitude** | 10 km | 13 km | 20 km |
| **Wavelength ($\lambda_x$) of Break** | 23 km | 15 km | 3 km |

Omitted from Table 1 are the data shown in Figure 7 of *Nastrom et al.* (1987) and Figure 7 of *Lilly and Lester* (1974). These figures depict an occasion when the spectral break occurred roughly at wavelength of 20 km in the altitude range of 14 to 20 km; thus suggesting an altitude dependence which is at variance to the trend shown in Table 1. As will be discussed in Section 3.3, however, certain factors must be held constant before one can ascertain the actual altitude dependence as predicted theoretically by a cascade theory. This will be discussed in more detail below.

## 3. PREDICTIONS OF THE AVAILABLE THEORIES

### 3.1. The Quasi-Two-Dimensional Turbulence Theory (Q2DTT)

*Nastrom et al.* (1987) explain their Figure 6, which is our Figure 1, by means of quasi-two-dimensional turbulence. (Note that these data were taken in the presence of a strong gravity wave source.) The latter involves a "reverse cascade" from small to large scale. They refer to the 2-D turbulence discussions given in *Lilly* (1983) and *Gage* (1979); and this theory explains the $k_x^{-5/3}$ that they observe. *Nastrom et al.* (1987) explain the break in Figure 1 as being due to a spectral steepening caused by a $k$ dependent flux divergence around the scale where energy is inserted into the reverse cascade. The source of this energy is "breaking waves" and the scale of the source is "related to the vertical scale of wave breaking". [This quote is from *Nastrom et al.* (1987), p. 3094, first line.] Thus, according to this theory, the scale where the break in the spectrum occurs depends upon only two controlling factors: (a) the vertical scale of wave breaking and (b) the scale range over which this energy is inserted. We now turn to the question of what this theory predicts for the altitude dependence of the break in the spectrum. We first assume that the scale of wave breaking controls both the size of the $k$ range over which energy is inserted into the cascade and the scale of energy insertion. In this case the altitude dependence of the break in the spectrum will depend completely on the vertical scale of the breaking waves. The next question is "What determines this scale?" To answer this question we turn to the theory of clear air turbulence in the atmosphere due to breaking waves as given in *Beer* (1974) in Section 4.7. On page 189 he states that the vertical scale of wave breaking, $\delta Z$, is given by $\lambda/\pi$ and thus we see that it depends on $\lambda$, the vertical wavelength of the breaking wave. It is well known that, due to the fall off of density with altitude, the vertical wavelength scale grows with

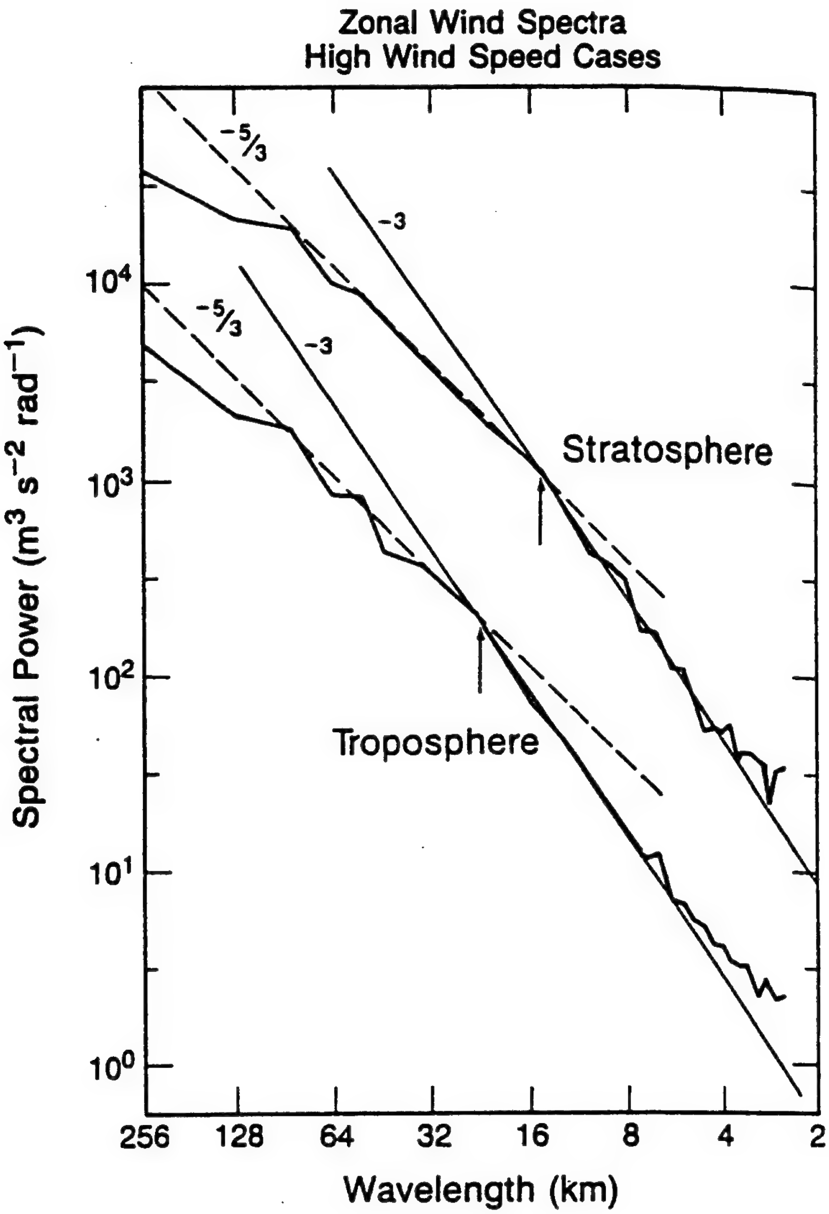


Figure 1. Horizontal wavenumber spectra of horizontal winds after *Nastrom et* al. (1987). (Strong winds over mountains are present, constituting a strong wave source.) The tropospheric altitude is 10 km and the stratospheric altitude is 13 km.

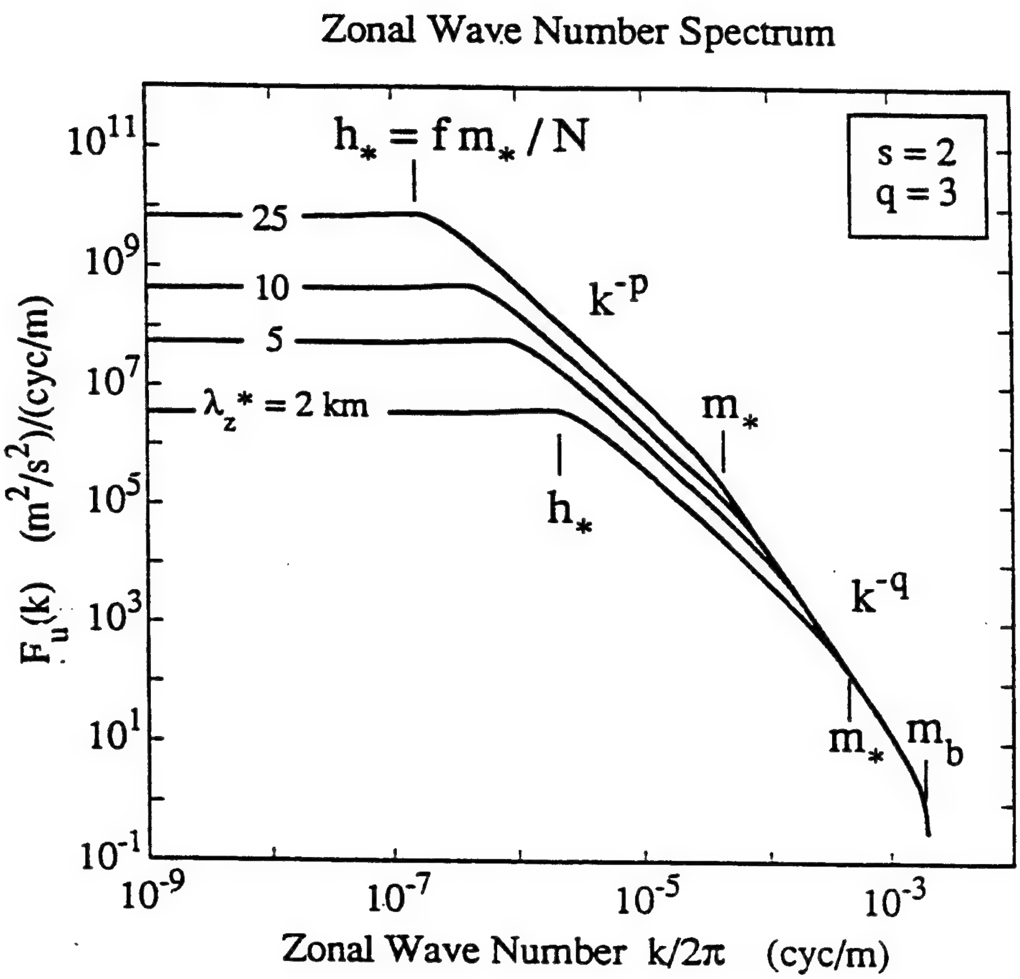


Figure 2. Horizontal wavenumber spectrum of horizontal winds after *Gardner et al.* (1993). This figure shows that the scale of the slope transition occurs at $m_* = 1/\lambda_{z*}$ where $\lambda_{z*}$ is the wavelength of the slope transition in the vertical wavelength spectrum in his theory.

altitude (*Smith et al.*, 1987). From this one can conclude that since the vertical scale of wave breaking increases with altitude, the scale of the spectral break in slope will also increase with altitude (according to Q2DTT).

### 3.2. Separable Gravity Wave Theories (SGWT) of *Gardner et al.* (1993)

Figure 2 shows the prediction for a one-dimensional horizontal wavenumber spectrum of horizontal velocities from the theory of gravity waves in *Gardner et al.* (1993). (This theory does not depend on nearby sources.) It is their Figure 5. Note that there is a -2 slope (close to minus 5/3) for lower wavenumbers followed by a minus 3 slope for higher wavenumbers. The quantity $m_*$ in this figure stands for the "characteristic vertical wavenumber" of *Smith et al.* (1987). As the latter paper explains, $m_*$ is the lowest wavenumber for saturation effects to be present and this $m_*$ decreases with altitude. But, in Figure 2, $m_*$ also denotes the location of the break between the -2 and -3 sections of the PSD. The prediction of this theory is, therefore, that the spectral break in slope would move toward larger wavelengths (i.e. smaller wavenumbers) as the altitude of the measurement increases. Thus the qualitative prediction of SGWT is the same as that of Q2DTT. Quantitatively, however, the prediction of SGWT is off by a large factor. For example, in the stratosphere $2\pi / m_* = \lambda_{z_*} = 2-5\,\text{km}$, whereas in Figure 1 and Table 1 we see that the stratospheric break in the spectrum occurs at 15 km. While it is not impossible to imagine that this theory could be modified so as to be in better quantitative agreement with the facts, this still remains to be seen.

The more recent theory of *Gardner* (1994), i.e. DFT, is completely mute on the subject of spectral breaks, and therefore is of no help in the present context. In other words Figure 1

conflicts with DFT; thus one could already regard DFT (at least in its present form) as a non-viable theory since it conflicts with non-controversial data from several sources.

### 3.3. The Saturated Cascade Theory (SCT) Predictions

As has been mentioned, a wave cascade is hypothesized in *Dewan* (1997), as well as in earlier versions (*Dewan*, 1979; 1991; 1992; 1994). This cascade in some ways resembles the inertial range of turbulence and it predicts a similar $\varepsilon^{2/3}k_x^{-5/3}$ dependence for one-dimensional horizontal wavenumber spectra of horizontal winds. The symbol $\varepsilon$ gives the dissipation rate and it does not depend on wavenumber. However, as W. Hocking (1996) has suggested in private conversation [see also *Dewan* (1997), Sections 3 and 6.2.3], there is an initial "set up time" at the commencement of a cascade before the equilibrium condition can come into existence. In other words, during the initial stages of the cascade (which goes from large scale to small scale) only the largest scales are involved. Only at later times do the smaller scales become involved. To make this clearer, consider the analogy between a wave cascade and a water cascade. The latter consists of water spilling down a series of steps. In the analogy the higher steps represent the larger scales or wavelengths of the waves, while the lower steps represent the smaller scales. As the water cascade starts, the lower steps would remain dry, while only the upper steps would be wet. The water would descend one step at a time until, finally, the lowest step would be reached. At that point the cascade would reach equilibrium, that is to say, as much water would enter the top step (or, by analogy, the largest scale) as would leave the bottom step (smallest scale). The drain at the bottom of the steps would, in the wave analogy, play the role of turbulent dissipation, $\varepsilon$. The turbulence cascade phenomenon was first described in a famous poem by L.F. Richardson as follows: "big whirls have little whirls that feed on their velocity, and little whirls have lesser

whirls, and so on to viscosity (in the molecular sense)". In the case of the wave cascade, an explanation was given in some mathematical detail in *Dewan* (1979) along with the following analogous poem: "big waves have little waves that feed on deformation, and little waves have lesser waves to turbulent dissipation (in the eddy sense)". In *Dewan* (1979), the "deformation" is caused by wave induced shears, and these in turn were shown to be able to feed smaller waves, and so on in a self-similar fashion. Notice that the energy transfer did not involve any form of wave "breaking".

The objective of going into such detail about this analogy is to explain the breaks in the spectra of Figure 1. The break occurs at the scale of the current "end point" of the cascade as it is "setting up". At sufficient distance from the source there would be no break. Left out of this account is why the slope at higher wavenumbers is -3, but this is beyond the scope of the present report.

What does this theory predict in regard to altitude dependence of the spectral break wavenumber? Its sole prediction is that, as the wave field propagates away from the source, the cascade evolves, and the wavenumber of the break becomes higher over time (and hence with the increase of distance from the source). Obviously, if the measurement aircraft is horizontally displaced from the source, the separation distance between them must be calculated on the basis of both the altitude and the horizontal displacement. For simplicity, let us assume that the source of the waves is located directly below the altitude of the measurements. With this assumption the cascade will extend to smaller scales as the wave field ascends in altitude; and, for this reason, one can expect the spectral break to occur at smaller scales at higher altitudes, assuming all other things are equal. Table 1 suggests that this is what takes place. Note, however, that if the location of the source of gravity waves were above the altitude of the measurement, one

would find the opposite altitude dependence. The controlling factor here is the distance from the source; for the latter controls the time available for the cascade to progress during this "set up" phase. In the case where the source is located at a great horizontal distance, there would be ample time for the "set up" to occur, and hence there would be no spectral breaks. The latter seems to explain why spectral breaks do not seem to be observed over the ocean (or, if they are, why they seem to be so rare, due to the fact that there are fewer GW sources over water).

Next we consider the previously mentioned observations of *Lilly and Lester* (1974). These seem to suggest a trend that contradicts Table 1. Their measurements suggest that the spectral break wavenumber decreases with altitude. Can this observation be consistent with the SCT prediction? The answer is yes provided that the gravity wave source is less horizontally displaced from the aircraft in the case of *Lilly and Lester* (1974) than it was for the case of *Nastrom et al.* (1987). The main point is that a test of SCT requires a controlled experiment in which the horizontal source to aircraft distance is held constant. In *Dewan* (1997) a quantitative study of this problem is given and there it is explained that, in the case where the GW source is directly below the aircraft, the separation distance can be estimated from a vertical group velocity given by the "characteristic wavelength" (see *Smith et al.*, 1987 for a definition) divided by the inertial period. This factor may also need to be controlled due to possible changes in the vertical characteristic wavelength over time. To do that, one could conduct the experiment over a single day during which there was essentially no change in GW source strength, i.e. no significant change in the velocity of the wind over the mountains, or significant weather change.

Incidentally it is worth noting that a closer examination of Figure 7 in *Lilly and Lester* (1974) does not suggest a spectral break in slope that changes scale with altitude between 14 km and 18 km. Unfortunately the length of the flight segments in *Lilly and Lester* (1974) are

considerably shorter than those found in *Nastrom et al.* (1987). The latter had segments as long as 1,200 km, whereas the former did not have segments much longer than 200 km. This caused the spectra of the former to be limited to the -3 slope regime and hence not to clearly show the -5/3 slope regime. This underscores the importance of duplicating the long trajectories found in *Nastrom et al.* (1987) in the experiment proposed in this report.

It is possible to quantitatively calculate the change in the wavenumber of the spectral break as a function of altitude by using the formalism of *Dewan* (1997). There it is shown that one can estimate the rate of ascent of the gravity wave cascade and thus the time available to the cascade for its development. Given this time, one can furthermore estimate the "distance" traveled by the cascade in "scale space" and hence quantitatively estimate the altitude dependence of the spectral break. In this report, however, we are concerned with the prior question of which of the available theories are qualitatively correct.

### 3.4 Predictions of the Garret-Munk Empirical Model as Modified by van Zandt

A number of empirical models for internal wave spectra in the upper ocean were published by Garrett and Munk during the 1972-1981 time period. *van Zandt* (1982) adapted this type of model for the atmosphere. In particular (van Zandt, private communication, 2001) he has pointed out that the publication of *Garrett and Munk* (1975) predicts a spectrum for horizontal wavenumber spectrum that has a slope of –2 for a small wavenumber and –5/2 for a large wavenumber. The van Zandt modification would make it –5/3 and –3 respectively (based on observation.) The equation on page 292 of *Garrett and Munk* (1975) implies that the wavenumber for transition from one slope to the other would be determined by the ratio of $N$, the Brundt frequency, to $\omega_i$, the inertial frequency. Therefore, the altitude dependence of the

transition scale would depend on the altitude dependence of this ratio according to this Garrett, Munk, van Zandt (GMV) model.

A summary of the predictions of all of these models is found in Table 2.

Table 2. Predictions of Altitude ($z$) Dependence of the Length Scale or Wavelength Where –5/3 Slope Starts to Steepen to a More Negative Slope

| | | |
|---|---|---|
| 1 | O2DTT* | Length scale increases with $z$ |
| 2 | SCT* | Length scale decreases with $z$ |
| 3 | SGWT* | Length scale increases with z |
| 4 | DFT* | Length scale constant for all $z$ |
| 5 | GMV⁺ | Length scale proportional to $N(z)$ |

* See Introduction for acronym definitions.

\+ Garrett Munk model (1975) as modified by van Zandt (1982).

## 4. THE EXPERIMENTAL TEST

The purpose of the experiment would be to obtain horizontal wind fluctuation measurements along long horizontal trajectories by means of an aircraft in the manner that was responsible for Figure 1 from *Nastrom et al.* (1987). [See also *Nastrom and Gage* (1985) and *Gage and Nastrom* (1986).] These measurements would be made at several altitudes on the same day with the same aircraft and equipment. Since the goal is to measure the spectral break as a function of altitude, this would entail 3 or 4 long horizontal trajectories at widely separated altitudes ranging from 8 km to 20 km. Two things are of great importance for this experiment: (a) there must be a strong source of gravity waves near the aircraft and (b) this source must be located nearly directly below the aircraft. In *Nastrom et al.* (1987) an effective source of gravity waves (responsible for Figure 1) was strong wind over mountains, therefore the proposed experiment should duplicate this situation as closely as possible. As was previously mentioned, *Bacmeister et al.* (1996) used an instrumented ER-2 to measure the spectrum in question at 20-km altitude. For the proposed experiment a similar aircraft would be required. The control experiment would consist of repeating this procedure over the same mountains when the winds over them were very weak. Thus we envision an experiment which would involve an aircraft like the ER-2 which could measure 3 or 4 constant altitude paths in the troposphere and stratosphere of lengths comparable to those observed by *Nastrom* et al. (1987) who used path lengths of order 1,000 km and conducted their experiments along the Rocky Mountains in western USA.

*Bacmeister et al.* (1996) used a highly unusual method to obtain their spectra. This procedure used "wavelets"; and not only is this procedure not well understood in regard to potential artifacts, it is also ill-suited for finding the locations of the spectral breaks. The method

used in *Nastrom et al.* (1987), which is based on the Fourier transformation, is far better for our purpose.

This experiment promises to go a long way towards settling the question of spectral break behavior as a function of altitude under controlled conditions.

## 5. CONCLUSION

There are five theories available to explain horizontal wavenumber power spectral densities of horizontal wind fluctuations. They are: (a) Q2DTT or quasi-two-dimensional turbulence theory (*Gage*, 1979; *Lilly*, 1983); (b) SCT or saturated cascade theory (*Dewan*, 1997); (c) SGWT or separable gravity wave theories (*Gardner et al.*, 1993); (d) DFT or diffusive filtering theory (*Gardner*, 1994) and (e) GMV or Garrett Munk model (1975) as modified by VanZandt (1982). The Q2DTT and SGWT predict that when one is near a strong source of gravity waves there is a spectral break in this power spectrum, and that it occurs at a smaller wavenumber when the altitude of the measurements is increased. On the other hand, SCT predicts that the opposite would occur, i.e. the wavenumber increases with altitude. Table 1, based on existing experiments, favors the latter. DFT, at least as it is now portrayed, is mute on this subject. This report has outlined an experimental way to determine whether the Q2DTT and SGWT are viable or if the SCT is the one that is viable. The same experiment could also prove whether or not SCT is quantitatively viable, if it should turn out that it passes the qualitative test. (See *Dewan*, 1999.) Finally, it could turn out that the altitude dependence of the position of the break depends, at a given latitude, exclusively upon the buoyancy frequency, in which case the only viable theory would turn out to be the GMV theory.

A recent paper by *Cho and Lindborg* (2001) is of great interest in connection with the possibility of the quasi 2-D turbulence mentioned above in the section on Q2DTT. They showed strong evidence, based on experimentally measured structure functions, that such a cascade is "ruled out". While I agree that their evidence is compelling, it is well known that it is always beneficial in science to acquire as much independent evidence as possible about such matters.

After all, as has already been mentioned above, *Cho et al.* (1999b) presented evidence in support of Q2DTT.

Without having alternative theories to test, the mere presence of a "break in the spectrum", which is discussed in this report, would be of little interest. In the present situation, however, the behavior of this break with altitude could determine which of five theoretical approaches are truly viable. For this reason it would be very desirable if those who perform experiments of this type would bear this in mind in the future when they design their programs.

## REFERENCES


Bacmeister, J.T., S.D. Eckermann, P.A. Newman, L. Lait, K.R. Chan, M. Loewenstein, M.H. Proffitt, and B.L. Gary, Stratospheric horizontal wavenumber spectra of winds, potential temperature, and atmospheric tracers observed by high-altitude aircraft, *J. Geophys. Res.*, **101**, 9441-9470, 1996.

Beer T. *Atmospheric waves*, John Wiley and Sons, 1974.

Cho, J.Y.N. and E. Lindborg, Horizontal velocity structure functions in the upper troposphere and lower stratosphere, 1. Observations, *J. Geophys. Res.*, **106D**, 10223-10232, 2001.

Cho, J.Y.N., Y. Zhu, R.E. Newell, B.E. Anderson, J.D. Barrick, G.L. Gregory, G.W. Sachse, M.A. Carroll, and G.M. Albercook, Horizontal wavenumber spectra of winds, temperature, and trace gases during the Pacific Exploratory Missions, 1. Climatology, *J. Geophys. Res.*, **104**, 5697-5716, 1999a.

Cho, J.Y.N., R.E. Newell, and J.D. Barrick, Horizontal wavenumber spectra of winds, temperature, and trace gases during the Pacific Exploratory Missions, 2. Gravity waves, quasi-two-dimensional turbulence, and vertical modes, *J. Geophys. Res.*, **104D**, 16297-16308, 1999b.

Crooks, W., et al., *Project HICAT*, AD-847-497, Natl. Tech. Inf. Serv., Springfield, VA, 1968.

Dewan, E.M., Stratospheric wave spectra resembling turbulence, *Science*, **204**, 832-835, 1979.

Dewan, E.M., Similitude modeling of internal gravity wave spectra, *Geophys. Res. Lett.*, **18,** 1473-1476, 1991.

Dewan, E.M., The saturated-cascade model for atmospheric gravity wave spectra and the wavelength-period (W-P) relations, *Geophys. Res. Lett.*, **21**, 817-820, 1994.

Dewan, E.M., Saturated-cascade similitude theory of gravity wave spectra, *J. Geophys. Res.*, **102D**, 29799-29817, 1997.

Dewan, E.M., *Direct experimental evidence for an atmospheric gravity wave cascade*, AFRL-VS-TR-1999-520, NTIS no. ADA-372-696. Available from NTIS via internet address: www.NTIS.gov or by telephoning the NTIS: 1-800-553-6847.

Dewan, E.M., W. Pendleton, N. Grossbard, and P. Espy, Mesospheric OH airglow temperature fluctuations: a spectral analysis, *Geophys. Res. Lett.*, **19**, 597-600, 1992.

Gage, K.S., Evidence for $k^{-5/3}$ law inertial range in mesoscale two-dimensional turbulence, *J. Atmos. Sci.*, **36**, 1950-1954, 1979.

Gage, K.S. and G.D. Nastrom, Theoretical interpretation of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft during GASP, *J. Atmos. Sci.*, **43**, 729-740, 1986.

Gao and Meriwether, Mesoscale spectral analysis of in-situ horizontal and vertical wind measurements at 6 km, *J. Geophys.Res.*, **103D**, 6397-6404, 1998.

Gardner, C.S., Diffusive filtering theory of gravity wave spectra in the atmosphere, *J. Geophys. Res.*, **99**, 20601-20622, 1994.

Gardner, C., C. Hostetler, and S. Franke, Gravity wave models for the horizontal wavenumber spectra of atmospheric velocity and density fluctuations, *J. Geophys. Res.*, **98**, 1035-1049, 1993.

Garrett, C. and W. Munk, Space-time scales of internal waves; a progress report, *J. Geophys. Res.*, **80**, 291-295, 1975.

Lilly, D.K., Stratified turbulence and the mesoscale variability of the atmosphere, *J. Atmos. Sci.*, **40**, 749-761, 1983.

Lilly, D.K. and P.F. Lester, Waves and turbulence in the stratosphere, *J. Atmos. Sci.*, **31**, 800-812, 1974.

Nastrom, G.D. and K.S. Gage, A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft, *J. Atmos. Sci.*, **42**, 950-960, 1985.

Nastrom, D., D. Fritts, and K. Gage, An investigation of terrain effects on the mesoscale spectrum of atmospheric motion, *J. Atmos. Sci.*, **44**, 3087-3096, 1987.

Smith, S.A., D.C. Fritts, and T.E. van Zandt, Evidence of a saturated spectrum of atmospheric gravity waves, *J. Atmos. Sci.*, **44**, 1404-1410, 1987.

van Zandt, T.E., A universal spectrum of buoyancy waves in the atmosphere, *Geophys. Res, Lett.*, **9**, 575-578, 1982.